


THE EFFECT OF THE EARTH'S RADIATION BELTS
ON AN OPTICAL SYSTEM*

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ABSTRACT

A photoelectric optical imaging system has survived one year in the earth's radiation belts with no measurable (<20%) change in sensitivity. The system passes through all of the radiation belts twice every 64 hours, and when in their most intense regions experiences a noise level of about 400 photons/second which is several orders of magnitude less than that of other photoelectric systems now operating in the belts. The number and energy distribution of incident particles is calculated and then combined with shielding estimates to give the total energy absorbed in the optical elements.

The effects of radiation on optical systems in general is briefly summarized, with emphasis on recent work of others.

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From presently available data it is often difficult to predict the performance of an optical system in space. The charged particles trapped in the earth's radiation belts will bombard optical systems causing damage and noise, but the actual particle flux that will be encountered is uncertain to an order of magnitude and useful laboratory measurements of radiation damage and fluorescence of common optical materials is scarce. It is therefore of interest to report on the successful endurance of one particular optical system which has been passing through all of the earth's radiation belts for more than one year with no measurable change in sensitivity. Also, in any rapidly developing field such as space optics, it is useful to collect and report on some of the latest results of others.

In the first part of the paper, the effect of particle radiation on optical systems in general will be briefly summarized, with emphasis placed on crucial or recent measurements relevant to the use of optics

in space. Then a detailed and quantitative description of the "Photoelectric Camera" on the OGO-I satellite will be given, including estimates of flux encountered, shielding, system noise level in the heart of a radiation belt, and comparison of its performance with expectation.

I. OPTICAL SYSTEMS IN GENERAL

Charged particle radiation in space interferes with an optical system in the following ways: It sputters atoms away from the surface of mirrors reducing their reflectivity. It reduces the transparency of lenses and filters by disrupting the crystal lattice structure or by ionizing atoms within the solid. It causes small changes in the index of refraction. It causes lenses and filters to fluoresce or scintillate, introducing unwanted light into system. And, of course, high energy particles have collisions with the detector introducing noise. Some of these effects will now be briefly discussed.

A. Reflection Optics

Except at low altitude, the problem of sputtering from mirrors appears to be negligible in the ultraviolet, visible, and the near infrared. Hass and co-workers¹ have studied aluminum mirror surfaces

coated with a magnesium fluoride layer approximately 250A thick to prevent oxidation. These mirrors have high reflectivity for wavelengths longer than 1100A. This reflectivity is not damaged by electron bombardment equivalent to ten years in the worst part of the radiation belts, nor by heavy ultraviolet fluxes, nor by moderate proton bombardment (5 Mev protons, $10^{12}/\text{cm}^2$). However, at altitudes of less than 300 km, oxygen and nitrogen in the upper atmosphere is expected to cause considerable damage² due to ablation.

Also negligible is erosion by micrometeorites of the thin coatings often applied to mirrors and lenses. Neel³ showed on the first orbiting solar observatory that whatever slight erosion and sputtering does occur (at altitudes of 500 Km.) far less than 100A of material is removed from the surface in one year.

Apparently the main problem with using mirrors in space is getting them into orbit in clean condition. In particular, oil from vacuum systems tends to deposit on mirror surfaces during pre-launch testing. Even if the oil film does not at first absorb light in the wavelength region of interest, the film can be chemically changed by particle bombardment in space and may then cause absorption.

B. Transmission Optics

Contrary to the situation with mirrors, there are many problems with the use of transmission optics in space. The main problem is fluorescence which occurs in many optical materials when placed in a particle radiation field. While it is often possible to shield the vulnerable optics against the incident protons and electrons, the secondary x-rays generated in the shield material continue on to the optics with little degradation and many interact there releasing light. This can be a severe problem for experiments measuring low light levels. Several astronomical experiments which are presently in orbit see quite different effects from the radiation belt ranging from less than 400 extraneous photons per second for one system, to greater than 10^5 photons per second for another. These are extra photons actually counted by the detector when in the most intense region of the belt. These noise levels are presumably due to fluorescence. That even higher noise levels than this could occur in an optical system is obvious from the fact that, in the heart of the earth's artificial radiation belt, electrons of energy greater than 1/2 Mev are incident at rates of approximately $10^8/\text{cm}^2\text{-sec}$ and there are far larger

quantities of lower energy electrons incident which can generate secondary x-rays.

Aside from avoiding the belts entirely, the only practical solution is to carefully choose transmission optics which fluoresce either weakly or in wavelengths to which the detector is not sensitive. This is not easy in the vacuum ultraviolet. Both LiF and CaF₂ fluoresce in the very wavelength regions (1000-2000A) for which they are used. Sapphire and fused silica fluoresce slightly in the visible. A brief, but recent summary of fluorescence and damage in the ultraviolet will be given by Dunkelman and Hennes in their chapter of a forthcoming book⁴. A great deal of work remains to be done on the fluorescence of common optical materials with special emphasis being placed on reducing the intensity of fluorescent light by producing materials of the highest purity.

An additional problem in lenses and filters is radiation damage which permanently reduces the transparency of the material. An excellent summary of these problems in quartz and silica is given by Billington and Crawford⁵. Heath and Sacher⁶ have irradiated many of the materials commonly used in the ultraviolet and measured their transmission from 1050A to 3000A.

Because of the ability of MgF_2 , BaF_2 , and Al_2O_3 to survive bombardment by 2 Mev electrons in doses of $10^{14}/\text{cm}^2$, Heath and Sacher conclude that these materials have the greatest potential for space applications in the ultraviolet. They find the familiar, LiF , to be particularly vulnerable to particle radiation damage. Transparency data in the visible and infrared has been collected by Gilligan and Elliot² for a large number of irradiated materials.

Finally, the problem of changes in index of refraction has been investigated by Malitson, et al^{7,8}. They find changes in index as large as one part in 10^4 at visible wavelengths in common optical glasses after irradiation with doses of 10^6 to 10^8 Rads* of Co^{60} gamma rays. These changes can last for periods of months at room temperature. This is already a serious difficulty for high resolution optical systems but the index of refraction would be expected to vary by even larger amounts at wavelengths near a radiation-induced absorption band.

One of the more radiation -- resistant materials

*The "Rad" is a measure of energy absorbed by a unit mass of irradiated material. One Rad = 100 ergs/gram.

is fused silica. In its purest forms (for example: "Supracil" of Englehardt Industries) it requires a dose⁵ in excess of 10^{19} energetic neutrons/cm² to reach maximum absorption at 2150A, (absorption coefficient, $\alpha \sim 300 \text{ cm}^{-1}$). However, the effect is not linear⁵ with dose and Heath and Sacher⁶ report a doubling of the absorption coefficient at this same wavelength to a value of $\alpha = .44 \text{ cm}^{-1}$ after a dose of only $10^{14}/\text{cm}^2$. This latter dose represents a year's exposure in a fairly bad orbit (circular, polar, 1400 Km altitude). If the sample be less pure, the required dose drops considerably and absorption in the visible also occurs. Further, if the material is very cold, Compton and Arnold⁹ have found another order of magnitude increase in damage.

Not nearly so much effort has been put into measuring the sensitivity of other optical materials to radiation damage. In particular, common filter materials badly need studying. Because of the complexity of these materials they are not of much interest to solid state physicists but they will probably be the most vulnerable part of an optical system.

II. THE OGO-I PHOTOELECTRIC CAMERA

On 5 September 1964 the first Orbiting Solar Observatory (OGO-I) was launched into a highly elliptical

orbit whose perigee altitude was about 350 kilometers and apogee altitude was about 149,000 Km. Because of its orbit this satellite passes through all of the earth's radiation belts once every sixty-four hours. The total amount of radiation encountered by this satellite in one year is typical of that received by a large number of other scientific satellites. Therefore, it will be of some general interest to see how an optical experiment on board this satellite performed.

A. Optical System Characteristics

The optical system on OGO-I which will be described is the "Photoelectric Camera" which forms images of the sky in visible and near-visible light and transmits these back to earth where they are reconstructed as pictures. Each of these pictures covers about 100 square degrees of sky with a resolution of one half degree. Figure 1 shows a cross section of the optical system and from the 35.3 cm length of the entire system any other dimension on the drawing may be estimated. The f/1.5 lens has four elements of which the first two are high purity fused silica and the next two CaF_2 . Light passes from the lens through any one of five filters in a wheel. These

filters can transmit either 3000A, 5000A, or 7000A each with a passband of 500A half width. The light comes to a focus on an S-20 cathode which is deposited on a thin, curved window of Corning 9741 U-V transmitting glass. Only the photoelectrons leaving one particular point on the cathode are allowed to proceed to the photomultiplier chain and be amplified. Output pulses from the tube are counted rather than being integrated into an average current. The image dissector tube was made by International Telephone and Telegraph Corporation under the name Star Tracker FW 143B. The optical system was designed to operate at very low light levels and the quantum efficiency at the center of the various wavelength bands ranged from 2% to 10%.

B. Charged Particle Fluxes

Of the charged particle fluxes encountered in space by far the most important are those in the earth's radiation belts. Cosmic rays are negligible because of their small numbers (10^8 particles/cm²-year). The solar wind normally contains particles of such low energies as to be of no interest and, while the higher energies associated with periods of solar activity might be of some importance, they are rare and will

not be considered here.

Figure 2 shows a cross section perpendicular to the earth's magnetic equator of the three commonly discussed radiation belts. The boundaries are chosen at the locus of points in space where the particle flux is only 1% of its value at the center of the belt. Of course, the size of the belts also depends on the energy threshold chosen so that it is not possible to draw one picture defining their boundaries. Nevertheless Figure 2 will suffice for general orientation. The artificial belt was created by a nuclear explosion in July 1962 and the number of particles in the belt is decaying with time. The proton belt is expected to decrease in intensity¹⁰ as we approach the maximum of solar activity in 1969; the decrease will be most pronounced at low altitudes where it may exceed an order of magnitude. The natural belt is known to be somewhat variable with time¹¹. In addition, the belts are not completely mapped at all energies and all regions of space. Thus any predictions of the flux that will be encountered by a satellite in orbit will be complicated to arrive at and rather unreliable. With these limitations in mind, an estimate was made of the charged particle flux incident on the OGO-I satellite.

Figure 3 shows the estimated total flux and spectrum of protons incident on OGO-I. The ordinate, $\Phi(>E)$, represents the total number of protons greater than energy, E , which were incident on one square centimeter of the satellite surface in the first year. Each "data-point" is based on flux values reported in the literature^{11,12,13,14} at various positions in space. The values presented on this figure are the result of numerical integrations around the orbit of OGO-I to get its time-averaged dose. This is not a straightforward task since published radiation belt fluxes don't extend over the whole volume of interest. It was often necessary to extrapolate to other regions of space based either on theory or measured spatial distributions at another energy. Results are thus somewhat subjective, although it is felt that the errors introduced by this necessary procedure are unlikely to exceed the order of magnitude uncertainties in the published radiation belt data itself.

Figure 4 shows a similar curve for the natural and artificial electrons. As before, the spectrum shows a steep increase toward lower energies. Each point plotted on the figure refers to the natural radiation belt and is derived from the literature^{11,12,15,16}

in the same manner described above for the protons. A smooth curve was then drawn through the rather scattered points. The curve labeled "artificial belt" is derived in a different way. It is based on the E 8 grid collected by Dr. W. M. Hess of Goddard Space Flight Center which gives fluxes in the artificial belt at various energies including their decay with time. This curve is more accurate than the others presented, perhaps being as good as a factor of two. Because the perigee distance of OGO-I changed substantially in the first year, it was actually necessary to generate a curve like this for four different times during the year. The curve shown here is the time-weighted sum of these four results.

It is interesting to note that while the radiation dose received by OGO-I is typical¹⁷ of that which would have been received in the orbits of most scientific earth satellites in the year 1965, it is also within a factor of 500 of the worst possible dose that could be received in orbit. This is shown in Table I for protons of energy >4 Mev and electrons $>\frac{1}{2}$ Mev. In this table, two circular orbits have been chosen to lie in the most intense regions of either the proton belt or the artificial electron belt.

C. Flux Absorbed by Optics

The charged particle flux actually reaching the optical elements of the OGO-I photoelectric camera will be less than shown on Figures 3 and 4 due to shielding by other parts of the spacecraft. To understand how important this would be, four representative locations were chosen and the total mass of material between each location and infinity was calculated as a function of solid angle. Table II shows the results for the most poorly shielded and best shielded points, namely, the outside surface of the lens and the outside surface of the dissector tube (labelled "Cathode Face Plate"). No attempt was made to estimate shielding when it was greater than about 5 g/cm^2 since only a negligible number of incident particles would be energetic enough to penetrate.

Having a rough picture of the shielding, it is easy to get an order of magnitude estimate of the total energy lost by particles in the optics. Energy is of interest rather than the number of particles because the energy determines the degree of radiation damage and fluorescence to be expected. First, the established range of protons and electrons in

aluminum¹⁸ was used to calculate how many of the incident particles would penetrate the various thicknesses of material shown in Table II. Isotropic flux was assumed, and the small error made by assuming all shield mass to have the stopping power of an equivalent mass of aluminum was ignored. Then, an integral was performed over the energy of all particles reaching the optics. In the integration all particles penetrating the shield were taken to still have their original energy. Since energy loss is peaked at the end of a charged particle's range, not much error is introduced here either. Table III shows the resulting estimate of how much energy was deposited by protons and electrons in the lens and cathode face plate.

The lens energy is presented in two parts to show that most of its dose arrives in the unshielded cone of .72 steradians through which the camera looks at the sky. Since most of the energy is carried into this unshielded cone by very low energy particles which can penetrate only fractions of a millimeter into the lens, heavy damage may occur in the surface layer of a lens used in space. Any energy deposited by particles having less than 10 Kev of energy is not included in

Table III because the number density of lower energy particles in space has not yet been established.

D. Observed Effects of Belts on Photoelectric Camera

Inspection of the data from the photoelectric camera shows that no large change in the overall sensitivity of the system has occurred in the first year. Throughout the year the minimum intensity in the green picture was always within the range 3000 to 7000 counts/sec. (To obtain a homogeneous sample, data was eliminated in certain well-understood cases when the earth or moon was in the picture, or the satellite was not in direct sunlight.) There being no tendency of values in this range to increase or decrease as the year progresses, it is considered statistically unlikely that any change in camera sensitivity greater than 20% occurred. The day-to-day variations within the range 3000-7000 counts/sec are difficult to remove since they are caused by changes in the amount of sunlight scattered into the camera by other parts of the spacecraft. There are no plans for trying to understand these changes in detail since the very location of some parts of the spacecraft is in doubt, due to failures in initial deployment.

The best evidence for increased noise levels when the satellite was passing through the radiation belts comes from data obtained in a series of eclipses in March 1965. During these times, of course, no scattered sunlight entered the system and it was possible to observe much smaller changes in camera response. In the most intense regions of the artificial radiation belts (as calculated from satellite location, and Hess' E 8 grid mentioned earlier) the camera sensed only 400 extra counts per second through its green filter. For comparison, the dimmest part of the sky causes a response of 800 counts/second as seen through this same filter.

This noise level is much lower than that observed by several other experiments launched on later satellites, OSO-II and OGO-II. All these experiments contain photomultiplier tubes and some transmission optics. The least noisy of these, the Zodiacal Light experiment of Ney, reports¹⁹ a noise level equivalent to 10^5 photons/sec being counted by the detector. These large noise levels can be partially understood in terms of photocathode area: Photomultiplier tubes typically have of the order of several square centimeters of cathode area to generate noise, whereas the image

dissector tube used on OGO-I had an effective area of only $.003 \text{ cm}^2$ at any given instant. Thus the dissector tube system would be expected to be quieter in the ratio of cathode areas (1000 times); roughly speaking, it is.

III. CONCLUSIONS

The fact that no change in the sensitivity of the OGO-A camera can be detected is consistent with the radiation dose estimates made in Section IIA and the measured properties of fused silica used in the lens. By summing the appropriate numbers in Table III, one finds that an energy of about $7.9 \times 10^{12} \text{ Mev/cm}^2$ was absorbed by the front of the lens. This is not a severe dose of radiation for pure fused silica. Even when one allows another order of magnitude to account for the low temperature, -25°C , of the lens in space, this number is still comparatively low considering that this material should sustain a dose of 10^{16} Mev/cm^2 before showing a 10% drop in transmission.

Since there are no ground measurements of radiation damage with which to compare the filters and phototube, we can merely state that they have survived a dose of about $0.6 \times 10^{12} \text{ Mev/cm}^2$ without noticeable change. This is the value given in Table III

for the cathode face plate, since additional calculations, not presented here, showed that all of these internal optical parts were shielded about equally well.

In conclusion, we see that it is possible to operate a sensitive optical system for long periods of time in a radiation belt environment. With only moderate shielding transmission optics can still be used, especially if the most exposed element is made of high purity fused silica, or some other radiation-resistant material.

Noise levels to be expected in the belts are highly variable -- depending critically on the degree of shielding, the amount of fluorescence, and the effective area of detector. Because of their very low noise levels, even in the radiation belts, image dissector tubes are especially suitable for optical systems which scan the sky or scan a spectrum. They should be more widely considered as substitutes for the more conventional system which uses rotating mirrors or gratings, and a large area cathode which is uniformly illuminated by means of a field lens.

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CAPTIONS

Fig. 1 - OGO Photoelectric Camera, Cross-section

Fig. 2 - Approximate Location of Radiation Belts,
Cross-section

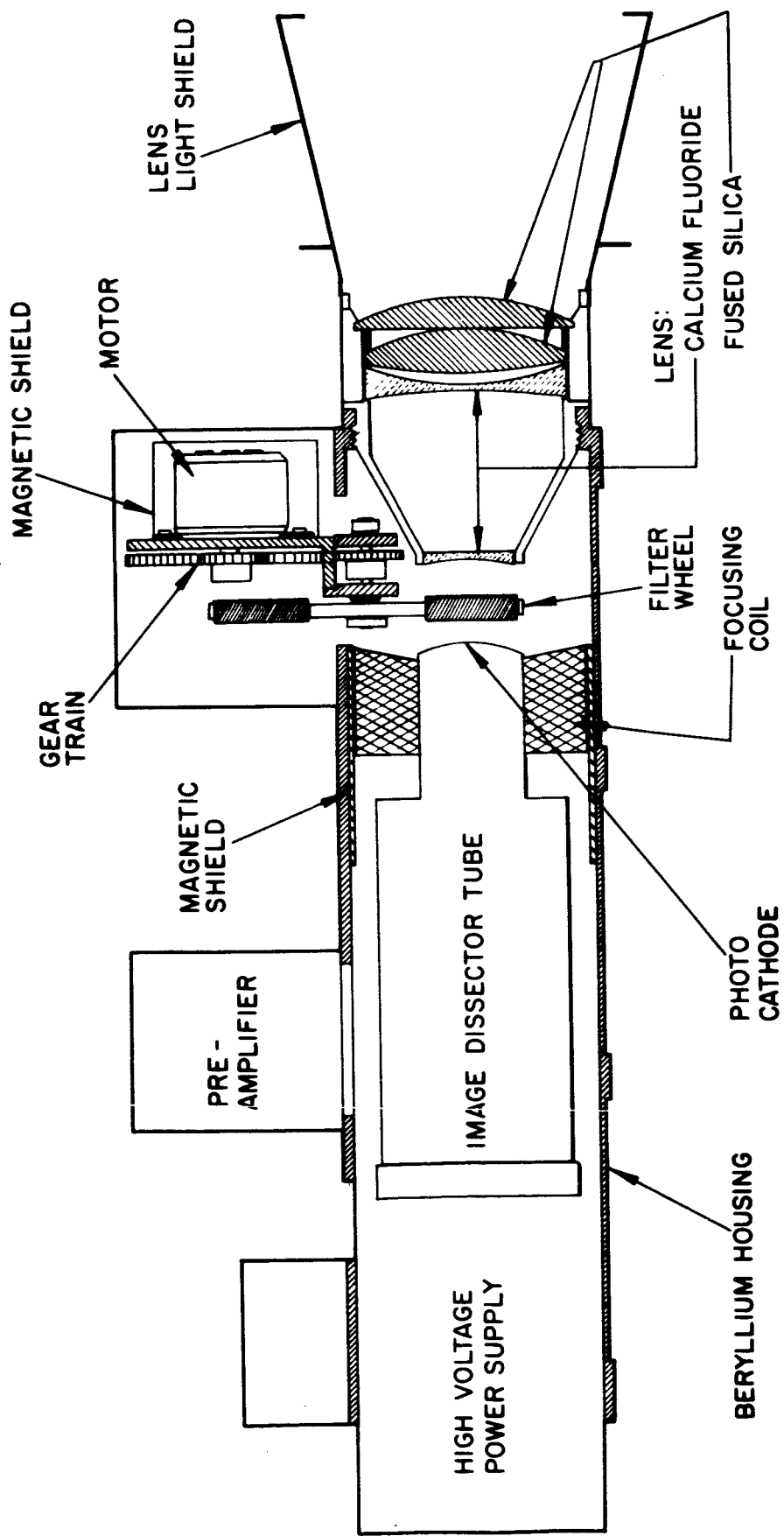
Fig. 3 - Protons Incident on OGO-I First Year

Fig. 4 - Electrons Incident on OGO-I First Year

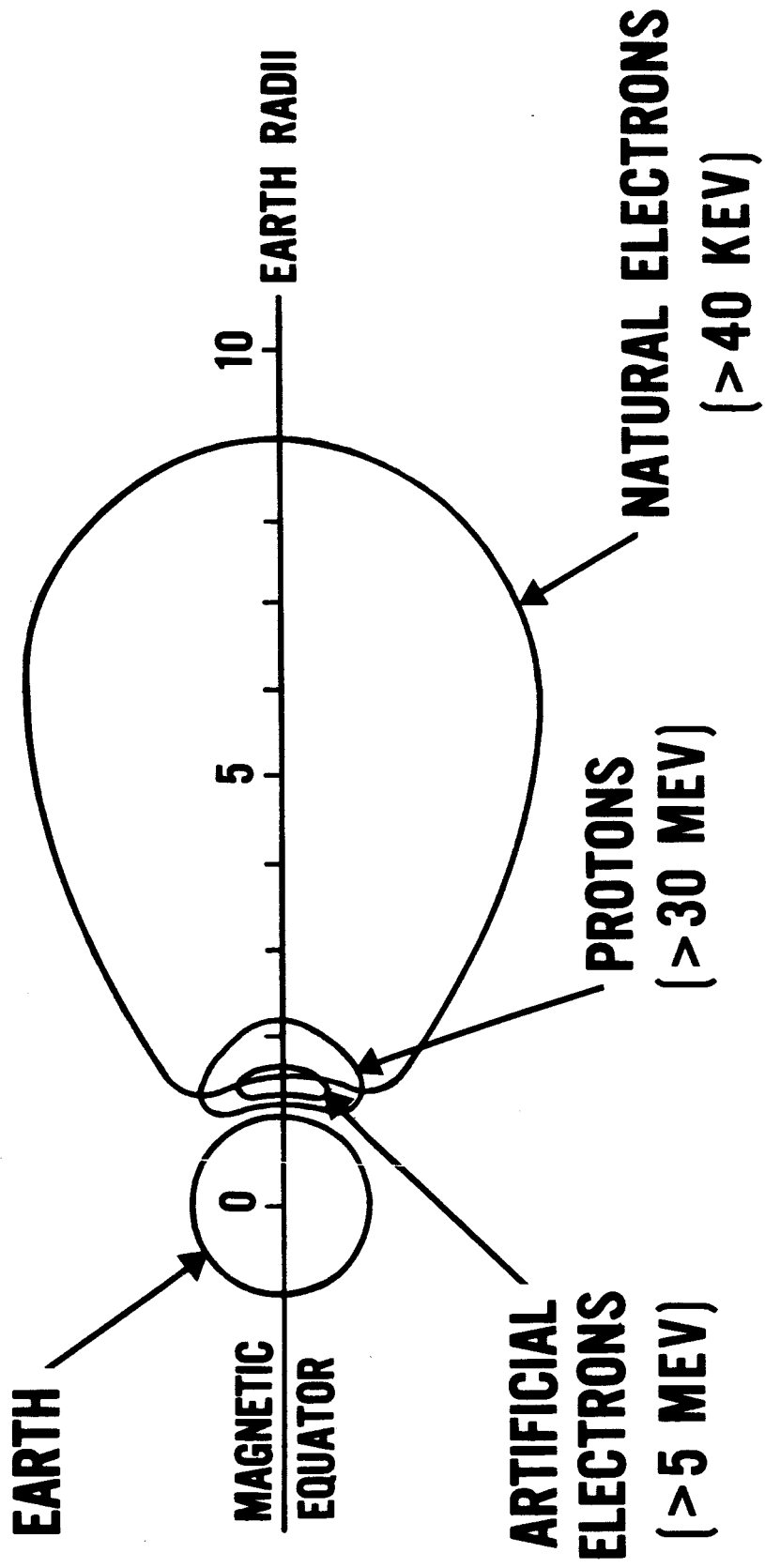
Table I - Annual Flux of Penetrating Particles Received
in Several Orbits

Table II - Shielding of Two Locations in Camera

Table III - Energy Absorbed in First Year by Two
Optical Elements

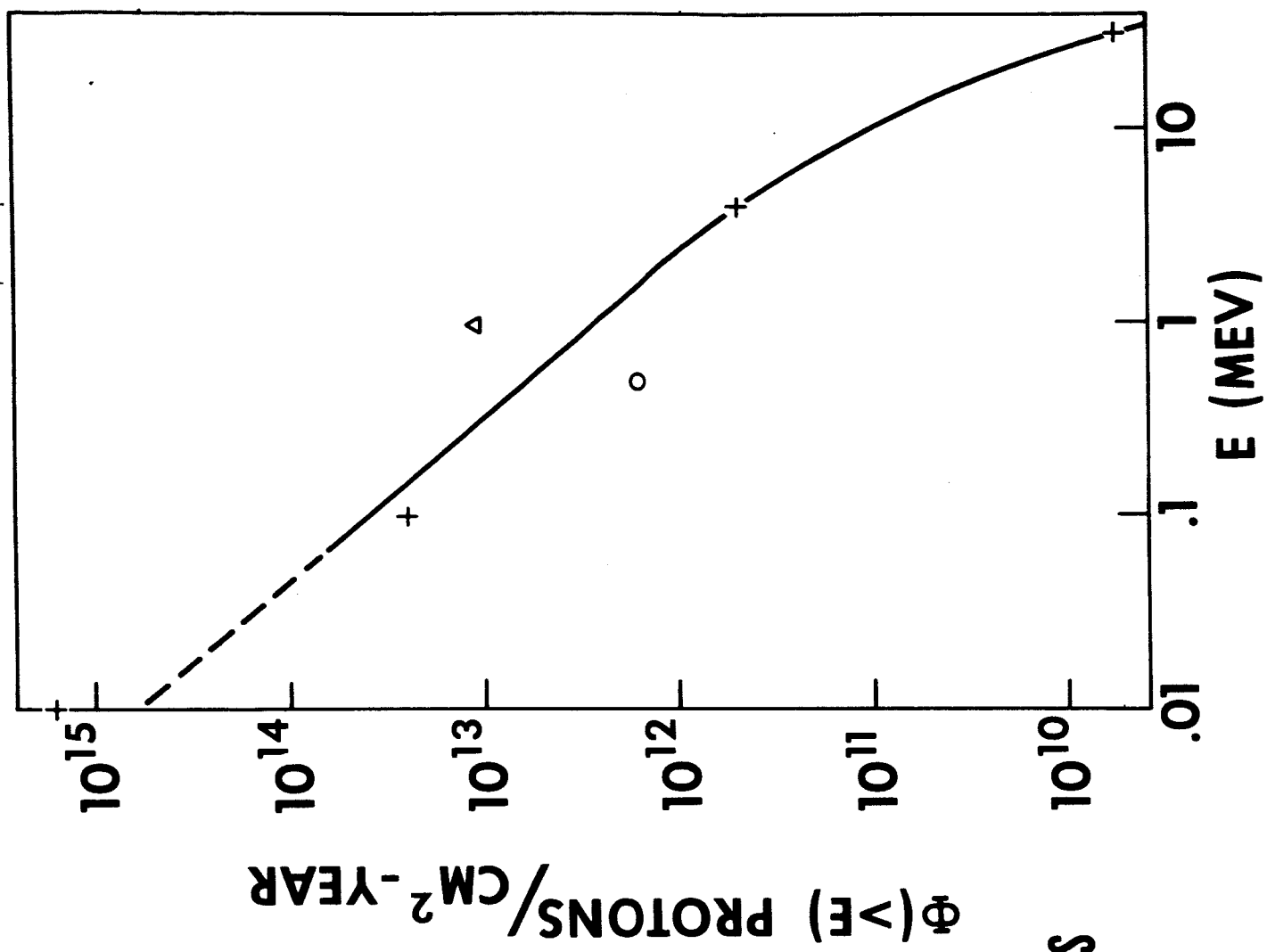


OGO photoelectric camera, cross section - right view



PROTONS INCIDENT
 ON OGO-I
 FIRST YEAR

- + HESS, ET. AL
- o FRANK, VAN ALLEN, HILLS
- Δ FILLIUS & McILWAIN



ELECTRONS INCIDENT ON OGO-I FIRST YEAR

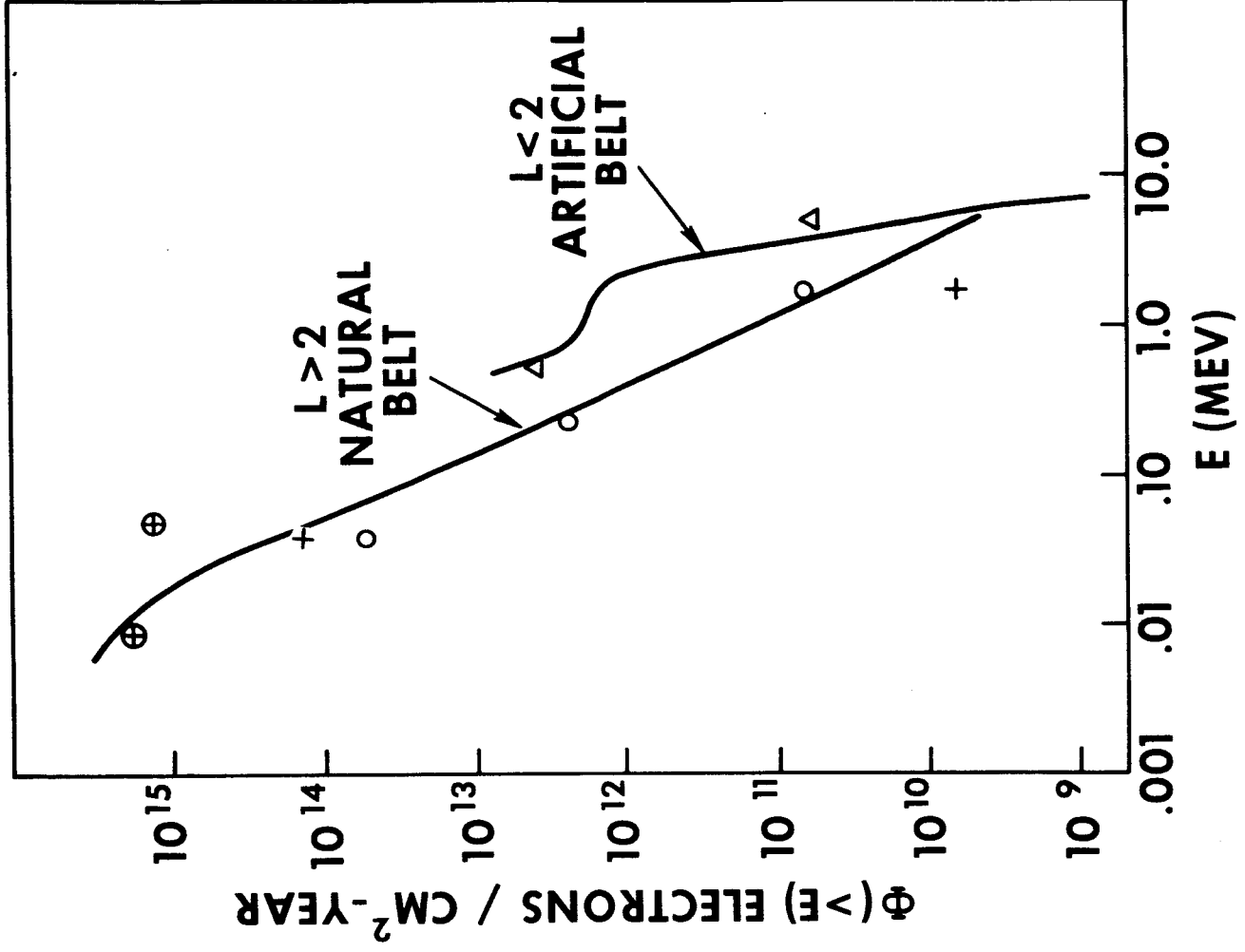
NATURAL BELT

⊕ PIZZELLA, DAVIS,
WILLIAMSON

+ HESS

Δ McILWAIN

○ FRANK, VAN ALLEN,
HILLS



ANNUAL FLUX OF PENETRATING PARTICLES

(September 1964 - September 1965)

	ORBIT TYPE		
	ECCENTRIC (OGO-I)	CIRCULAR (Max. Protons)	CIRCULAR (Max. Electrons)
PERIGEE ALTITUDE (Km.)	350 - 6800	5000	3000
APOGEE ALTITUDE (Km.)	149,000 - 143,000	5000	3000
INCLINATION	32° - 39°	0°	0°
PROTON FLUX (#>4Mev/cm ² -yr)	0.5 x 10 ¹²	100 x 10 ¹²	25 x 10 ¹²
ELECTRON FLUX (#>1/2Mev/cm ² -yr)	.1 x 10 ¹⁴	.6 x 10 ¹⁴	50 x 10 ¹⁴

SHIELDING OF TWO LOCATIONS IN CAMERA

LENS		CATHODE FACE PLATE	
Solid Angle (% of Sphere)	Shielding (grams / cm ²)	Solid Angle (% of Sphere)	Shielding (grams / cm ²)
5.7	0	18.9	1.2
38.2	.37	5.3	2.
2.2	.38	25.8	> 2.
1.6	1.0	50.0	> 6.
8.2	3.5	100%	
1.1	3.6		
2.8	4.7		
40.2	> 5.		
<u>100.%</u>			

ENERGY ABSORBED FIRST YEAR

	FROM PROTONS	FROM ELECTRONS
LENS - Unshielded Cone	1.6	3.7
LENS - All Other Directions	.37	2.2
CATHODE FACE PLATE	.05	.53

Units: $10^{12} \text{ Mev/cm}^2 = 1.6 \times 10^6 \text{ ergs/cm}^2$